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SHERIDAN PARK RESEARCH COMMUNITY
MISSISSAUGA, ONTARIO, CANADA L5K 1B3 • (416) 822 4111 • TELEX 06-982311

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Development of an Emission Control System for Underground Diesel Powered Equipment

FINAL REPORT 2580/2

for

CANMET, Energy Mines and Resources Canada,
Ottawa, Ontario.

CONTRACT REPORT NO. OSQ78-00018

Under DSS Contract No. OSQ 78-00018

Part 2

Performance Data

A. Lawson

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1. ABSTRACT

Part 2 of this report describes the performance of a catalyst/venturi scrubber test rig for reducing particulate emissions from a Deutz F6L 714 diesel engine derated for underground use. The design parameters of the venturi scrubber developed during the course of the project are recorded in Part 1.

Particulate collection efficiencies of the scrubber were, at best, 55%. This result indicates that the collection complexity is probably too great for consideration in a metal mine, but might be justified in coal mine application where flame proofing of diesel engines is required.

A. Lawson
Principal Scientist
Dept. of Environmental Chemistry

AL/EWS/MP/yp
March 29, 1979.

2. INTRODUCTION

The desire to increase the number of diesel units used in underground workings in order to increase productivity, together with the corresponding economic limitations controlling any significant increase in ventilation rates, and the general desire to improve the quality of the mine atmosphere, has led to the need for development of an economic, efficient, and practically acceptable emission control device for underground diesel powered equipment.

Diesel emissions of concern are CO, NO_x, SO_2/H_2SO_4, particulate matter and hydrocarbons. Recent studies carried out by the U.S. EPA (1) have shown that certain diesel generated hydrocarbons (generally high boiling) exhibit positive results for Ames tests of mutagenic activity. This has placed greater importance on the determinations of the condensible hydrocarbon content of diesel exhaust than has previously been considered.

It has become apparent, that in order to control the complete array of diesel emissions a systems approach is required, involving advanced, combined, emission control components and techniques.

Examples of such combined systems include:

- EGR/catalyst/Venturi water scrubber
  [NO_x/CO, THC/90% Particulates, SO_2, H_2SO_4]
- EGR/catalyst/low energy pass through water scrubber/ filtration device
  [NO_x/CO, THC/50% Particulates, SO_2, H_2SO_4/final clean up for Particulates, SO_2/H_2SO_4]
- Water emulsification/catalyst/low sulphur fuel
  [NO_x, Particulates/CO, THC/SO_2, H_2SO_4]
- Catalyst/Venturi water scrubber with chemical additive to the water for NO_x control
  [CO, THC/Particulates, SO_2, H_2SO_4, NO_x]

Each component of the combined systems has specific capability in terms

of control efficiency of the various contaminant emissions, as identified in parenthesis above.

No single engine or emission control combination is clearly identifiable as superior to any other for general application to underground diesel powered equipment. In some mining environments, NO_x may be considered of greatest significance as a potential health hazard (in potash mines, for example). In others, particulate emission may be of greatest concern (in uranium mining operations, for example, where radon gas may adsorb on respirable diesel particulate).

The most important aspects of the studies in this field are therefore to provide the data necessary to evaluate the potential of various engine and emission control options, so that mine operators may be able to select the equipment most suitable to their needs.

It is expected that screening tests of a number of emission control options, will be carried out under a USBM (United States Bureau of Mines) programme, information from which will be made available to CANMET under a free information exchange agreement.

This study therefore addresses the potential of a catalyst/venturi water scrubber as an emission control option for underground diesel powered equipment. The scrubber developed as part of this programme, has been applied to a Deutz Diesel F6L 714 engine, representative of an engine in common use underground.

The objectives of the study have therefore been to evaluate the maximum efficiencies of particulate collection which can be achieved with a catalyst/venturi scrubber test rig, and to assess its potential as an emission control option for underground diesel powered equipment. It is recognized that the catalyst/venturi water scrubber will not, in itself, have any effect on NO_x emissions. Therefore, tests have also been conducted on a laboratory scale, in a parallel ORF programme, of the potential of various chemical additives to the scrubber water, which might reduce the NO_x concentrations passing through the scrubber. This forms part of a strategy for NO_x control. Other possibilities exist in the form of water/diesel fuel

emulsion application, or water aerosol induction techniques, which are included in parallel studies of emission control options applied to both Deutz Diesel and Detroit Diesel engines (2) (3).

Part 2 of this study details the performance data obtained from a full scale test rig, employing venturi scrubber technology and featuring sufficient flexibility in operating parameters to allow investigation of the optimum conditions of operating the venturi in order to maximize the particulate collection efficiency. Part 1 of the study is provided as a separate report and details the development of the design parameters to be used in the construction of the scrubber.

3. ENGINE TEST RIG AND TEST METHODOLOGY

3.1 Test Rig

The engine selected for testing was a Deutz F6L 714 diesel engine derated to 93 kW at 2200 rpm. Valve clearances were set to manufacturers specifications, and the fuel injection timing of the Bosche injection system was set to 27° BTDC. The fuel used was Gulf Diesel 40, a No. 1 fuel typical of that used in underground diesel powered equipment. The fuel analysis is shown in Table 3.1.

A variable throat venturi scrubber was designed (4) to operate over a wide range of pressure drops for given engine load/speeds. The venturi incorporates a plunger which is allowed to travel within the venturi shell by means of a control cable. Design of the plunger and shell is such that the effective throat length is sufficient at all plunger positions.

The test rig constructed and applied to the exhaust system of the Deutz engine is shown in Figure 3.1. A photo of the control console is shown in Figure 3.2.

The rig was equipped with and without a PTX 623 platinum

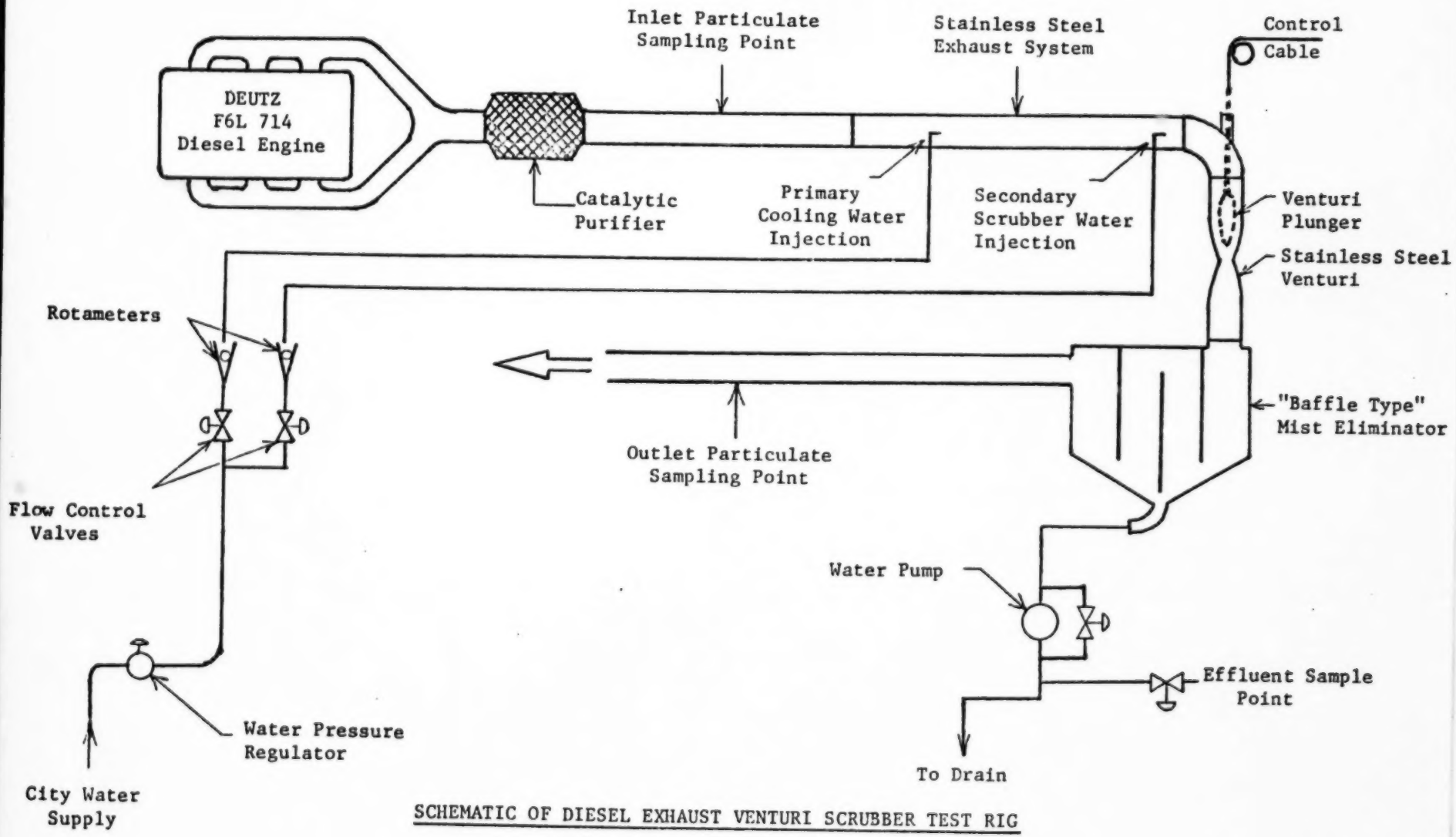
TABLE 3.1

GULF OIL CANADA LIMITED

DIESEL 40 FUEL SPECIFICATIONS

Specific Gravity	0.818
API Gravity	41.6
Colour	+20
Flash	138
Cloud °F	-52
Pour °F	-55
Distillation	
% Recovered	
I.B.P.	320
10	367
20	380
30	392
40	405
50	421
60	440
70	458
80	478
90	503
F.B.P.	545
Recovery	99.0
Residue	1.0
Loss	0.0
C/H Ratio	6.4
Carbon %	86.5
Hydrogen %	13.5
Sulphur %	0.10
Nitrogen ppm	17

Figure 3.1

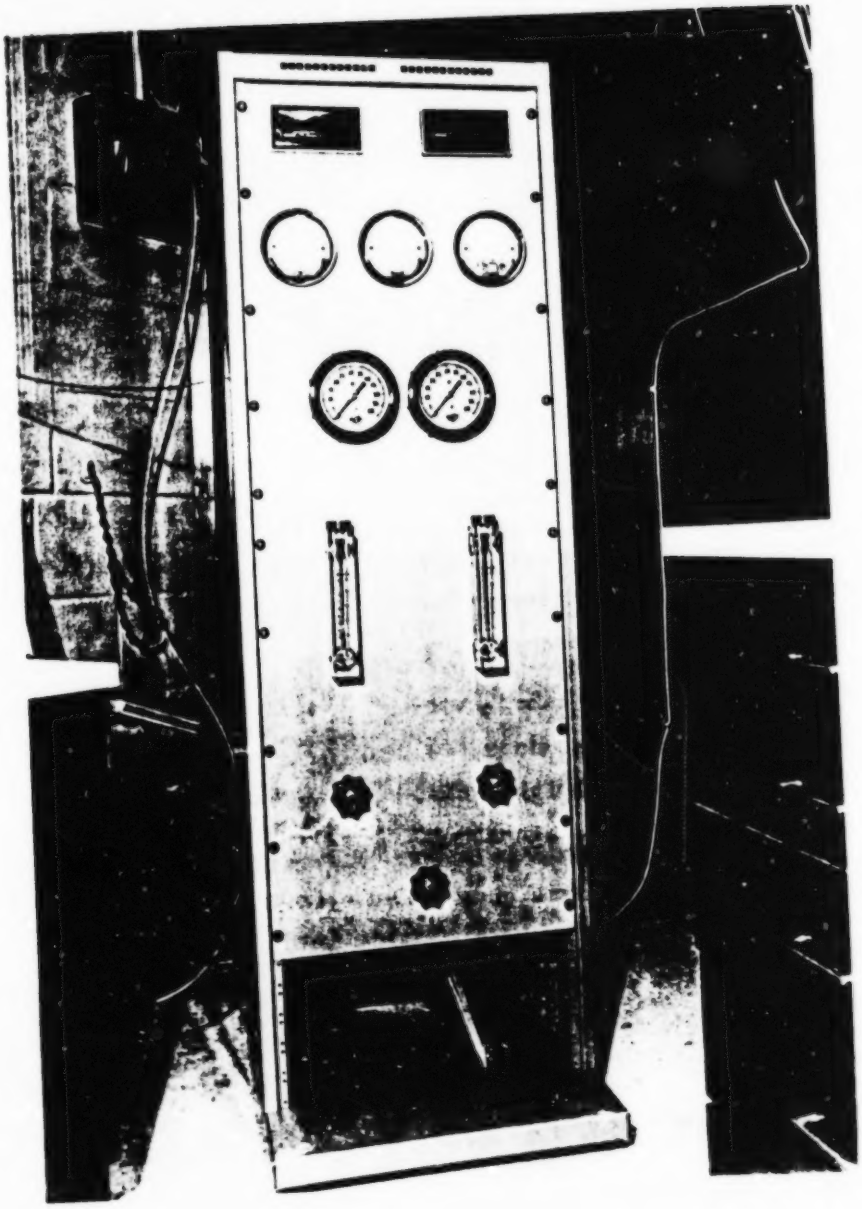


SCHEMATIC OF DIESEL EXHAUST VENTURI SCRUBBER TEST RIG

WITH CLEAN WATER INJECTION

FIGURE 3.2

CONTROL CONSOLE



monolithic catalytic exhaust purifier for comparative testing. The catalyst was installed in the exhaust system, about 1.5 meters from the exhaust manifold. Each exhaust bank was connected with a Y section of exhaust just upstream of the catalyst.

About 3 meters downstream of the catalyst, primary cooling water was injected whose function was to cool the exhaust prior to injection of the secondary scrubber water just upstream of the venturi throat. Downstream of the venturi a mist eliminator was incorporated to remove particulate water. This was of the baffle type designed to remove most of the condensed moisture, leaving the exit gas saturated at approximately 60 to 65°C.

Sampling points for collection of particulate material were located as follows:

Scrubber Inlet - downstream of catalytic purifier but upstream of primary cooling water injection

Scrubber Outlet - downstream of the mist eliminator. The mist eliminator prevented clogging of the filter with condensed water.

This arrangement allowed simultaneous sampling for particulate matter to be made during testing which was considered necessary to avoid errors due to day to day variations occurring with the basic engine emissions.

3.2 Test Methodology

Tests were carried out with and without the catalyst installed in the exhaust system to determine variations in particulate collection efficiency caused by the catalysts effect on hydrocarbon oxidation, and possible alteration to the wettability of the particulate matter.

City water at about 15°C was used in this set of feasibility

tests in both primary and secondary injection. This provides for a best case situation, since clean water is being supplied continuously as a scrubbing medium. In order to ensure smooth progress in the test programme, provision was also made to allow recirculation of the scrubber water via a heat exchanger as detailed in Part 1 of this report. This proceeded in parallel with design and construction of the plunger and throat assembly of the venturi. Tests with clean water injection, however, subsequently revealed that the particulate collection efficiencies observed did not justify progressing to a recirculation system. Instead the effort was directed towards improving the basic particulate collection efficiency with clean water injection. Primary water was added with sufficient quantity (2 litres/min) to cool the exhaust by evaporation without creating an excessive particulate water load to the cooled exhaust. The engine was operated throughout the test series at 2200 rpm and 93 kW load. The results of the particulate collection efficiency were insufficiently encouraging to merit testing at other load speeds. Instead additional effort was directed towards improving the basic collection efficiency at 2200 rpm and 93 kW.

Parameters varied during the course of the test programmes were, the pressure drop across the venturi (controlled by the position of the plunger and scrubber water added), the rate of secondary water injection, and design of the plunger and throat assembly including the angle of convergence and angle of divergence of the venturi throat.

4. INITIAL TESTING

Initial testing of the scrubber was complicated by the fact that particulate samples collected on the filters were found to contain iron oxide and brass contamination. This was confirmed with electron microprobe analysis of the particulate material, and could only result from material originating from the exhaust system. Discussion with Deutz engineers indicated that the material could not have originated from the engine. It was therefore necessary to replace the exhaust system with a

stainless steel one. This eliminated the problem, and reliable particulate samples could then be collected.

The effectiveness of the mist eliminator for removing condensed water was determined by examining the moisture content of the exhaust emitted from the mist eliminator and comparing it with the theoretical value for the moisture content of saturated exhaust at the operating temperature of the mist eliminator. Table 4.1 shows the results at a number of pressure drops across the venturi together with varying quantities of secondary water added upstream of the venturi. The temperature of the sampling point downstream of the mist eliminator was slightly higher than that at the mist eliminator, so the saturated vapour pressure of water at the latter temperature should be compared with the measured moisture content of the exhaust. It is clear that the mist eliminator is functioning efficiently as the measured moisture content is not greatly different from that of the saturated vapour pressure values.

5. ANALYTICAL METHODOLOGY FOR PARTICULATE SAMPLING

Particulate sampling of the engine exhaust is carried out using the E.P.A. Method 5 sampling technique with a train manufactured by Joy Manufacturing (see Figure 5.1).

The undiluted gases are sampled isokinetically and drawn through a short, heated, stainless steel probe to a 125 mm diameter Pallflex filter located in an oven maintained at > 120°C. The filtered gases are then bubbled through 250 ml of distilled water, divided between two Greenberg-Smith impingers sitting in an ice bath, dried with silica gel and delivered to a control module through an umbilical cord. The control module contains the diaphragm pump, gas meter, calibrated orifice, temperature monitors and controls.

The Pallflex T60A20 filters were conditioned prior to all weighings in a conditioning room maintained at 23°C and 50% R.H.

TABLE 4.1

MOISTURE REMAINING IN THE EXHAUST AFTER THE MIST ELIMINATOR AT THE OUTLET SAMPLING POINT

Venturi ΔP cm H_2O	Secondary H_2O ℓ/min	Mist Eliminator Outlet Exhaust Temperature °C	Temp. Sampling Point °C	*Moisture Calculated % $H_2O \frac{v}{v}$	Moisture Measured % $H_2O \frac{v}{v}$
100	15.7	50	54	14.8	16.9
50	8.8	50	54	14.8	16.3
100	15.7	58	59	18.7	22.9
50	8.8	58	59	18.7	22.8

* Calculated using water saturation vapour pressure at outlet sampling point temperature.

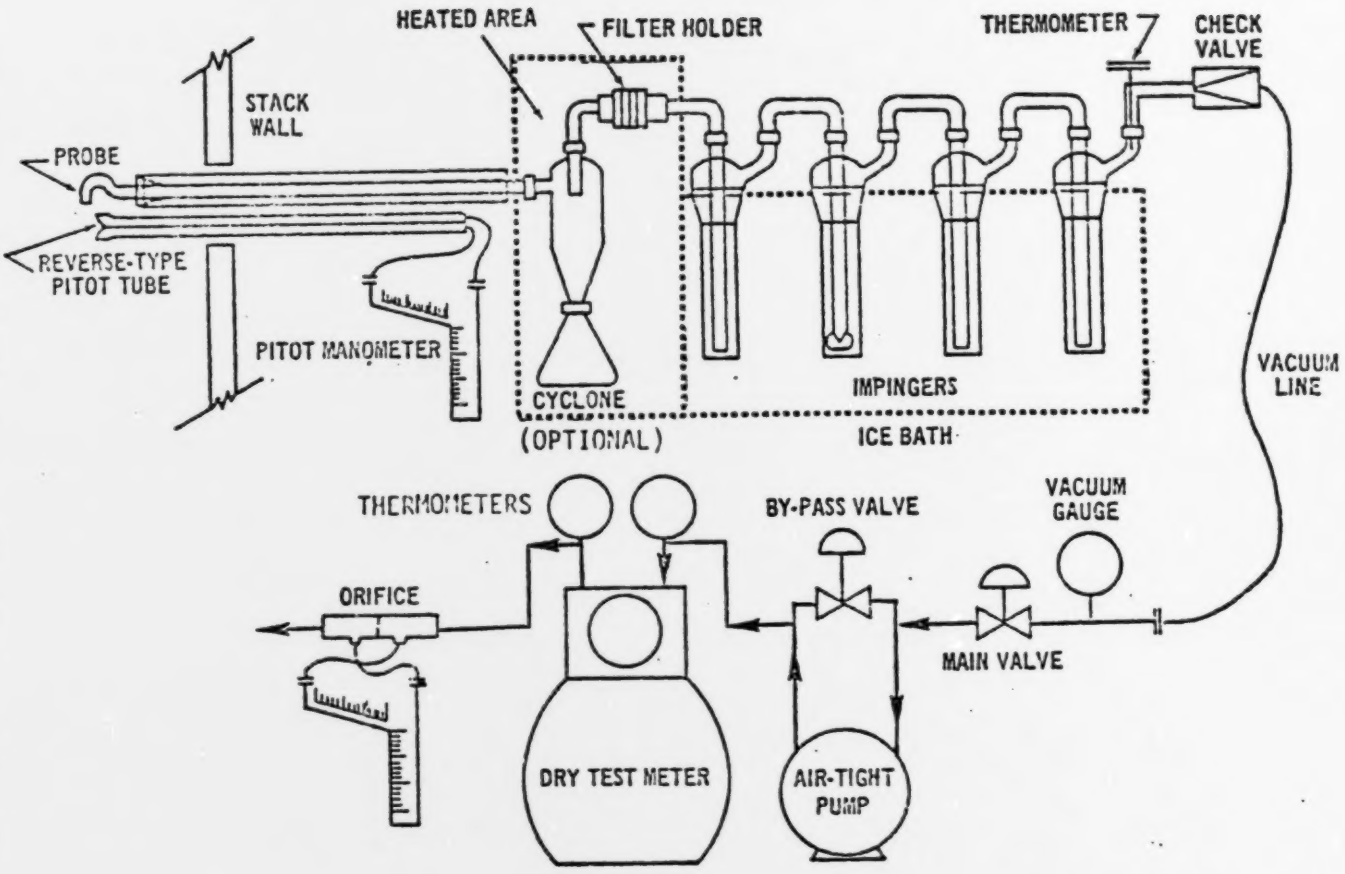


FIGURE 5.1 - SAMPLING TRAIN

After each test, the probe and nozzle were rinsed with a 50% isopropyl alcohol and cyclohexane mixture, and a brush was passed through the former to ensure the complete collection of particulate matter deposited in the probe. In the laboratory, the probe rinse is filtered to obtain an insoluble weight, and the filtrate is evaporated on a steam bath to determine the organic condensible portion of the probe rinse.

The total filter particulate was weighed and the filter extracted with cyclohexane in a Soxhlet apparatus to remove any soluble matter present on the filter. It is assumed that all the organic matter is removed as past tests have shown that no additional weight losses occur when the filters are re-extracted with dichloromethane. The amount of organic matter found on the filter depends on the filter temperature, which varies from test to test due to the exhaust gas, or sample, temperature. The impinger solutions are extracted with freon (Standard Methods for the Examination of Water and Wastewater, Method 502A) to measure any organic material which is condensed downstream of the filter. Therefore, condensible organic matter, as discussed in this report, comprises probe rinse and impinger condensibles and filter cyclohexane extractibles. The cyclohexane insoluble matter, which is essentially carbon, consists of the particulate portion of the probe rinse and the filter cyclohexane insoluble matter. Thus, total particulate matter is the sum of the insoluble and organic portions.

A series of particulate tests was done with a catalyst installed in the exhaust. It was found that a large amount of the filter cyclohexane insoluble matter was sulphate and associated water. A 50% isopropanol/water extraction was done on a regular basis for the catalyst testing series only, as the extractable matter for the non-catalyst tests was found to be in order of one percent, and was ignored. The insoluble matter remaining after these two extractions is considered to be carbon for the catalyst particulate tests.

6. BASELINE TESTS OF PARTICULATE EMISSION VARIATION WITH EXHAUST BACK PRESSURE

Increase in back pressure of the exhaust created by the presence of the venturi caused the particulate matter emitted from the engine to increase. Inlet particulate values to the scrubber were therefore always higher than those from a bare engine without exhaust treatment device. This must be taken into consideration in evaluating the overall effectiveness of the device. Table 6.1 therefore shows the effect of back pressure on particulate emissions for back pressures ranging from zero to 145 cm H_2O. Particulate matter is also broken down to show total particulate (collected at 32°F) together with cyclohexane insoluble matter and condensible hydrocarbons. Day to day engine variation is suspected to be the cause of the unusually high results obtained with tests 12 and 13, i.e. on that day it is believed that the zero back pressure particulate concentration was greater than 64.8 mg/m^3. Generally, back pressure increases particulate emission by as much as 1.5 times at a back pressure of 145 cm H_2O. At 100 cm H_2O back pressure the increase is about 1.2 times that of the zero back pressure values. It should also be noted that condensible organics remain essentially constant with increased ΔP, so that total particulate increases solely due to increase in cyclohexane insoluble material.

7. SCRUBBER TESTING FOR PARTICULATE COLLECTION EFFICIENCY WITH AND WITHOUT CATALYST

All tests were carried out at 2200 rpm, 93 kW, and with a primary water flow of 2 ℓ/min. At 100 cm water pressure drop and 15.7 ℓ/min scrubber secondary water flow, the collection efficiency for total particulate was found to be 44% without the catalyst and 53% with the catalyst. Table 7.1 shows the collection efficiency variation with decreased pressure drop and decreased secondary water flow. At lower pressure drops and lower scrubber water flows, the collection efficiency decreases. It is significant, however, that the catalyst does tend to

TABLE 6.1

THE EFFECT OF BACKPRESSURE ON UNCONTROLLED PARTICULATE EMISSIONS

ΔP cm H_2O	Total Particulate		Cyclohexane Insoluble Matter		Condensible Organic	
	mg/m^3	*Δ	mg/m^3	Δ	mg/m^3	Δ
0	64.8	1.0	58.1	1.0	6.7	1.0
50	88.2	1.4	81.3	1.4	6.9	1.0
	86.9	1.3	81.2	1.4	5.7	0.8
	93.1	1.4	86.1	1.5	7.0	1.0
	82.6	1.3	77.2	1.3	5.4	0.8
100	75.6	1.2	70.3	1.2	5.3	0.8
	86.5	1.3	80.5	1.4	6.0	0.9
	98.4	1.5	91.8	1.6	6.6	1.0
	96.5	1.5	87.7	1.5	8.8	1.3
	80.4	1.2	76.0	1.3	4.4	0.7
	80.8	1.2	73.8	1.3	7.0	1.0
145	105.7	1.6	100.3	1.9	5.4	0.8
	99.7	1.5	91.5	1.6	8.2	1.2

*Δ is multiplication factor for increased emission

TABLE 7.1

THE EFFECT OF A PTX CATALYST ON SCRUBBER

Description	ΔP cm H_2O	Secondary H_2O ℓ/min	Total Particulate			Insoluble Matter			Condensible Organic	
			Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlett mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3
---	100	15.7	97.4	54.6	44	89.7	50.6	44	7.7	4.0
PTX			85.1	40.3	53	77.2	34.7	55	7.9	5.6
---	100	8.8	80.4	50.1	38	76.0	44.7	41	4.4	5.4
PTX			84.2	50.5	40	73.0	39.1	46	11.2	11.4
---	50	15.7	87.5	54.0	38	81.3	49.7	38	6.2	4.3
PTX			80.0	48.0	40	69.6	38.9	44	10.4	9.3
---	50	8.8	87.9	58.9	33	81.6	56.0	31	6.3	2.9
PTX			85.2	64.2	25	76.7	50.1	35	8.5	14.1

increase the particulate collection efficiency, which confirms the earlier result obtained with simple pass through water scrubbers (5). The best collection efficiency of 53% is disappointing and not a great improvement over that obtained with simple water bath conditioners (5). In addition, if the effect of ΔP on increased carbon black formation is taken into the consideration, then the particulate values in the best case have changed from the bare engine value of 64.8 mg/m^3 to 40.3 mg/m^3, a decrease of 38%.

It should also be noted that at this load/speed, and accentuated by the increase in carbon black with increased exhaust back pressure, the condensible organic fraction of the exhaust is a very small component of the total particulate. Most of the values were close to the limit of detection, and hence the scatter in results makes it difficult to estimate how effective the scrubber was in collecting the condensible organic component of the particulate. In some engines where condensible organic emissions are high, the collection efficiency for organics will be of considerable importance as a result of recent considerations of the potential carcinogenic nature of such material.

8. ATTEMPTS TO IMPROVE COLLECTION EFFICIENCY

8.1 Computer Modeling

While testing was proceeding at ORF, parallel studies were being carried out at CANMET using computer modeling with the objective of trying to predict collection efficiencies for a given set of venturi design features and operating conditions. This study was based on papers by Boll (6), and Hollands and Goel (7) (8). Hollands and Goel used Boll's model and reduced it to a number of curves predicting particulate collection efficiencies for various pressure drops across the venturi. The particle size was however outside the range of the estimated size of diesel particulates, so the CANMET study addressed the problem of reducing the model to fit diesel

particle sizes. Details of the model are included in the Appendix to Part 1 of this study. The model was found to predict closely the collection efficiencies of the ORF designed venturi over the range of pressure drops and scrubber water flows detailed in Table 7.1. However, a choice of two models existed at higher pressure drops and water flows, one of which predicted that the collection efficiency would reach a maximum with increased scrubber water flow and decrease at higher water flows.

It was decided, therefore, that if clarification of the model could be achieved, predictions for optimum venturi design would be improved. Further tests were therefore carried out at increased pressure drops and scrubber water flows from that shown in Table 7.1. In order to operate the engine at the high back pressure of 145 cm of water, it was necessary to consult Deutz engineers, who recomemnded that temperature sensors be installed in each cylinder head to monitor individual cylinder temperatures. In this way, high temperature damage to the engine could be avoided by immediate shut down of the engine if excessive temperatures were monitored. In fact, no problems in this regard were encountered.

Tests with increasing pressure drop up to 145 cm H_2O are shown in Table 8.1 and Table 8.2 shows a comparable set of data with increasing scrubber water flow up to 34.6 ℓ/min. Both sets of tests were carried out without the catalyst installed. It is apparent that the collection efficiency continues to increase with increase in pressure drop across the venturi, and with increase in scrubber water flow. No maximum in collection efficiency occurs in this operating range. Collection efficiencies of about 50% without the catalyst suggest that about 60% efficiency can be achieved with the catalyst installed. At 145 cm H_2O back pressure, however, the particulate concentration at the inlet to the scrubber increased from the zero back pressure value of 64.8 mg/m^3 to 102.2 mg/m^3. Relative to the bare engine emission therefore the scrubber outlet concentration had

TABLE 8.1

THE EFFECT OF VARYING ΔP ON SCRUBBER COLLECTION EFFICIENCY

ΔP cm H_2O	Secondary H_2O ℓ/min	Total Particulate			Insoluble Matter			Condensible Organic	
		Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3
145	15.7	102.7	50.9	50	95.9	44.1	54	8.8	6.7
100	15.7	97.4	54.6	44	89.7	50.6	44	7.7	4.0
50	15.7	87.5	54.0	38	81.3	49.7	39	6.2	4.3
100	8.8	80.4	50.1	38	76.0	44.7	41	4.4	5.4
50	8.8	87.9	58.9	33	81.6	56.0	31	6.3	2.9

TABLE 8.2

THE EFFECT OF VARIOUS SECONDARY WATER FLOW RATES ON SCRUBBER COLLECTION EFFICIENCY

ΔP cm H_2O	Secondary H_2O ℓ/min	Total Particulate			Insoluble Matter			Condensible Organic	
		Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3
100	34.6	81.0	41.2	49	75.4	50.6	33	5.6	6.6
100	15.7	97.4	54.6	44	89.7	50.6	44	7.7	4.0
100	8.8	80.4	50.1	38	76.0	44.7	41	4.4	5.4
50	15.7	87.5	54.0	38	81.3	49.7	39	6.2	4.3
50	8.8	87.9	58.9	33	81.6	56.0	31	6.3	2.9

decreased by only 21%. The situation is a little better with the increased scrubber water flow of 34.6 ℓ/min, where the scrubber outlet concentration has decreased 36% relative to the bare engine particulate emission value.

Further attempts to improve collection efficiency were made by adding detergent to the scrubber water in order to improve wetability of the particles. The results are shown in Table 8.3 for tests carried out without the catalyst installed. No significant improvement in collection efficiency is evident as a result of adding the detergent. The average collection efficiency was 43%.

Tests were also conducted with the spray nozzles installed closer to the venturi throat, since it was thought that some stratification might occur from the original configuration where the nozzles were located on the other side of an elbow in the duct leading to the venturi. Tests carried out with the new configuration again showed no improvement in collection efficiency.

Final attempts to improve the particulate collection efficiency related to CANMET's recommendation for a modified plunger and throat configuration based on a paper by Hollands and Goel (9). Hollands and Goel proposed a procedure which should yield a design of venturi scrubber which is very close to optimal, that is, exhibit a minimum pressure loss for a given gas flow rate and particulate removal efficiency.

Accordingly, a modified plunger and throat assembly was constructed, details of which are included in Part 1 of this report dealing with design features. Testing of the new assembly was carried out using two formats, one with the same quantity of primary water, used in earlier experiments, to cool the exhaust prior to injection of secondary scrubber water, and the other employing a heat exchanger principle to cool the exhaust to below 350°C before the primary water injection. The purpose of this latter procedure was to take advantage of possible coagulation of the diesel particulate at that temperature.

TABLE 8.3

EFFECT OF ADDING DETERGENT TO SCRUBBER WATER ON SCRUBBER EFFICIENCY

Description	ΔP cmH_2O	Secondary H_2O ℓ/min	Total Particulate			Insoluble Matter			Condensible Organic		
			Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %
no additives	100	15.7	97.4	54.6	44	89.7	50.6	44	7.7	4.0	48
Triton X 100	100	15.7	85.8	51.7	40	76.7	45.9	40	9.1	4.8	47
RBS 25	100	15.7	83.4	47.3	43	77.0	42.4	45	6.4	4.9	23

TABLE 8.4

THE EFFECT OF MODIFIED PLUNGER DESIGN AND EXHAUST PRE-COOLER ON SCRUBBER COLLECTION EFFICIENCY*

Description of Plunger Design	Total Particulate			Insoluble Matter			Condensible Organic	
	Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3	Collection Efficiency %	Inlet mg/m^3	Outlet mg/m^3
Original ORF Design	97.4	54.6	44	89.7	50.6	44	7.7	4.0
Modified Plunger	90.8	49.1	45.5	87.5	45.3	48	3.3	3.8
Modified Plunger & Exhaust Pre-cooler	71.9	39.2	45.5	68.5	34.9	49	3.4	4.3

* All tests done at a back pressure of 100 cm H_2O and 19.7 ℓ/min secondary water.

The results of both tests are shown in Table 8.4. It is clear that the particulate collection efficiency is not significantly different from the earlier design.

A complete set of Composite Data Tables for all the tests performed are provided in Appendix I calculated on a mg/m^3, g/kW.hr, g/hr and g/lb fuel basis.

9. NO_x REMOVAL IN WATER SCRUBBERS

Although the efficiency of particulate removal, even in an optimized water scrubber is at best 55%, this may still be of interest for coal mine application where water scrubbers are required for flame proofing purposes. The water scrubber, by itself, or in combination with a catalyst, will not be able to control the complete array of diesel emissions since it will do nothing for NO_x control.

One option for including NO_x control is to employ a water/fuel emulsification technique, details of which are to be found in the report of a parallel study (2). Another option, however, is to employ chemical additives to the scrubber water. Accordingly, laboratory scale tests have been carried out to determine the potential of various chemical additives for collecting NO_x in the scrubber water. This, together with a catalyst and low sulphur fuel would result in control of the complete array of diesel emissions. The results of these tests are summarized in Appendix II. It is clear that whereas water alone has negligible effect on reducing NO_x concentrations, a number of chemical additives have potential for removing significant quantities of NO_x, particularly NO_2. This is of significance particularly when catalysts are employed, since it is recognized that catalysts can cause significant oxidation of NO to NO_2 to occur (5).

10. CONCLUSIONS AND RECOMMENDATIONS

1. The collection efficiency of a venturi scrubber for diesel

particulate, under the most favourable conditions of non-recirulated water injection, is about 45% without a catalyst and 55% when used in combination with a catalyst.

2. Tests at 2200 rpm and 93 kW indicate that the effect of exhaust back pressure is to increase the carbon black component of the particulate while the condensible organic component remains essentially unaltered.

3. The increase in particulate concentration with back pressure created by the venturi scrubber is such as to reduce the effective efficiency of removal of particulate to a value of about 37%, when compared with an uncontrolled engine.

4. The reason for the unexpectedly poor collection efficiency may lie in the size of the diesel particulate lying in a particularly difficult range for effective venturi scrubbing to take place. Particle size characterization carried out at CANMET suggests that bimodal distribution of particle sizes exists. The collection efficiencies observed may therefore be related to collection of the larger of the particles in the bimodal distribution range, leaving the smaller particles essentially untrapped. This would explain the similar collection efficiencies observed with a simple pass through water scrubber (5).

5. The results of the collection efficiencies indicate that the collection complexity is probably too great for consideration in a metal mine, but might be justified for coal mine application because of the requirement for flame proofing devices.

6. The use of a catalyst in combination with the scrubber improves the particulate collection efficiency. If NO_2 is produced as a result of catalyst use, the use of chemical additives is recommended to improve the collection efficiency of NO_x on the water scrubber. The employment of a water/fuel emulsification technique (2) also serves to reduce both NO_x and particulate and would improve emission characteristics if a catalyst is required as a component of the emission control system.

7. Testing is recommended on a water scrubber applied to an engine such as a Detroit Diesel 2-stroke which exhibits particulate emission characteristics with high condensible organic and low carbon black particulate components. If the collection efficiency for organics (particularly in the presence of detergent) is greater than that for carbon black, then use of a water scrubber (perhaps in coal mine application) in combination with the Detroit Diesel engine may result in an engine/emission control option having very low particulate emission characteristics.

11. REFERENCES

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APPENDIX I

Composite Tables of Test Data
Tables (a), (b), (c)

TABLE (a)

INLET AND OUTLET PARTICULATE MATTER EMISSION RATES FROM A VENTURI WATER SCRUBBER WITH VARIOUS PRESSURE DROPS ACROSS THE VENTURI, COMPOSITE TABLE

ΔP cm H_2O	Secondary Water ℓ/min.	Test No. and Location	Total Particulate Matter				Cyclohexane Insoluble Matter				Condensible Organic Matter			
			Conc.	Emission Rates			Conc.	Emission Rates			Conc.	Emission Rates		
			mg/m^3	g/kW.hr	g/hr	g/kg.fuel	mg/m^3	g/kW.hr	g/hr	g/kg.fuel	mg/m^3	g/kW.hr	g/hr	g/kg.fuel
145	15.7	25 Inlet	105.7	0.528	49.2	1.791	100.3	0.501	46.7	1.699	5.4	0.027	2.5	0.091
		Outlet	50.8	0.254	23.7	0.861	44.4	0.222	20.7	0.752	6.4	0.032	3.0	0.108
145	15.7	26 Inlet	99.7	0.498	46.5	1.689	91.5	0.457	42.6	1.550	8.2	0.041	3.8	0.139
		Outlet	51.1	0.255	23.8	0.866	43.9	0.219	20.5	0.744	7.2	0.036	3.4	0.122
50	15.7	14 Inlet	88.2	0.441	41.1	1.494	81.3	0.406	37.9	1.377	6.9	0.034	3.2	0.117
		Outlet	54.1	0.270	25.2	0.917	49.7	0.248	23.2	0.842	4.4	0.022	2.0	0.075
50	15.7	15 Inlet	86.9	0.434	40.5	1.472	81.2	0.406	37.8	1.376	5.7	0.028	2.7	0.097
		Outlet	53.9	0.269	25.1	0.913	49.7	0.248	23.2	0.842	4.2	0.021	2.0	0.071
50	8.8	16 Inlet	93.1	0.465	43.4	1.577	86.1	0.430	40.1	1.459	7.0	0.035	3.3	0.119
		Outlet	60.1	0.300	28.0	1.018	56.6	0.283	26.4	0.959	3.5	0.017	1.6	0.059
50	8.8	17 Inlet	82.6	0.413	38.5	1.399	77.2	0.386	36.0	1.308	5.4	0.027	2.5	0.091
		Outlet	57.7	0.288	26.9	0.978	55.3	0.276	25.8	0.937	2.4	0.012	1.1	0.041
0	0	27 Inlet	65.9	0.329	30.7	1.116	59.2	0.296	27.6	1.003	6.7	0.033	3.1	0.114
		28 Inlet	63.6	0.318	29.6	1.077	57.1	0.285	26.6	0.967	6.5	0.032	3.0	0.110

TABLE (b)

INLET AND OUTLET PARTICULATE MATTER EMISSION RATES FROM A VENTURI WATER SCRUBBER USING A DEUTZ F6L 714 DIESEL ENGINE WITH A PTX CATALYST

COMPOSITE TABLE

ΔP cm H_2O	Secondary H_2O ℓ/min.	Test No. and Location	Total Particulate Matter#				Cyclohexane Insoluble Matter				Condensible Organic Matter			
			Conc.	Emission Rates			Conc.	Emission Rates			Conc.	Emission Rates		
			mg/m^3	g/kW.hr	g/hr	g/kg.fuel	mg/m^3	g/kW.hr	g/hr	g/kg.fuel	mg/m^3	g/kW.hr	g/hr	g/kg.fuel
100	3.45	4 Inlet	86.3	0.431	40.2	1.462	79.3	0.396	36.9	1.343	7.0	0.035	3.3	0.119
		Outlet	42.0	0.210	19.6	0.712	36.3	0.181	16.9	0.615	5.7	0.028	2.7	0.097
100	3.45	5 Inlet	83.9	0.419	39.1	1.421	75.2	0.376	35.0	1.274	8.7	0.043	4.1	0.147
		Outlet	38.5	0.192	17.9	0.652	33.0	0.165	15.4	0.559	5.5	0.027	2.6	0.093
100	1.93	8 Inlet	87.7	0.438	40.9	1.486	77.9	0.389	36.3	1.320	9.8	0.049	4.6	0.166
		Outlet	49.3	0.246	23.0	0.835	40.7	0.203	19.0	0.690	8.6	0.043	4.0	0.146
100	1.93	9 Inlet	80.8	0.404	37.6	1.369	68.1	0.340	31.7	1.154	12.7	0.063	5.9	0.215
		Outlet	51.7	0.258	24.1	0.876	37.4	0.187	17.4	0.634	14.3	0.071	6.7	0.242
50	3.45	6 Inlet	80.0	0.400	37.3	1.355	69.6	0.348	32.4	1.179	10.4	0.052	4.8	0.176
		Outlet	48.0	0.240	22.4	0.813	38.9	0.194	18.1	0.659	9.1	0.045	4.2	0.154
50	3.45	7 Inlet*	--	--	--	--	--	--	--	--	--	--	--	--
		Outlet	48.1	0.240	22.4	0.815	38.5	0.192	17.9	0.652	9.6	0.048	4.5	0.163
50	1.93	10 Inlet	84.2	0.421	39.2	1.426	74.2	0.371	34.6	1.257	10.0	0.050	4.7	0.169
		Outlet	64.2	0.321	29.9	1.088	48.7	0.243	22.7	0.825	15.5	0.077	7.2	0.263
50	1.93	11 Inlet	86.2	0.431	40.2	1.460	79.1	0.395	36.9	1.340	7.1	0.035	3.3	0.120
		Outlet	64.2	0.321	29.9	1.088	51.4	0.257	23.9	0.871	12.8	0.064	6.0	0.217

* Inlet test not completed, and results not available.

Total Particulate levels do not include 50% iso-propanol/water extractable matter.

TABLE (c)

INLET AND OUTLET PARTICULATE MATTER EMISSION RATES FROM A VENTURI WATER SCRUBBER WITH A PRESSURE DROP OF 100 cm. OF WATER ACROSS THE VENTURI

COMPOSITE TABLE

Additional Test Description	Secondary Water ℓ/min.	Test Number and Location	Total Particulate Matter				Cyclohexane Insoluble Matter				Condensible Organic Matter			
			Conc.	Emission Rates			Conc.	Emission Rates			Conc.	Emission Rates		
			mg/m^3	g/kW.hr	g/hr	g/kg.fuel	mg/m^3	g/kW.hr	g/hr	g/kg.fuel	mg/m^3	g/kW.hr	g/hr	g/kg.fuel
--	34.6	23 Inlet	75.6	0.378	35.2	1.281	70.3	0.351	32.8	1.191	5.3	0.026	2.5	0.090
		Outlet	39.1	0.195	18.2	0.662	34.0	0.170	15.8	0.576	5.1	0.025	2.4	0.086
		24 Inlet	86.5	0.432	40.3	1.465	80.5	0.402	37.5	1.364	6.0	0.030	2.8	0.102
		Outlet	43.2	0.216	20.1	0.732	35.1	0.175	16.4	0.595	8.1	0.040	3.8	0.137
--	15.7	12 Inlet	98.4	0.492	45.8	1.667	91.8	0.459	42.8	1.555	6.6	0.033	3.1	0.112
		Outlet	56.5	0.282	26.3	0.957	52.4	0.262	24.4	0.888	4.1	0.020	1.9	0.069
		13 Inlet	96.5	0.482	45.0	1.635	87.7	0.438	40.9	1.486	8.8	0.044	4.1	0.149
		Outlet	52.6	0.263	24.5	0.891	48.8	0.244	22.7	0.827	3.8	0.019	1.8	0.064
		20 Inlet*	80.8	0.404	37.6	1.369	73.8	0.369	34.4	1.251	7.0	0.035	3.3	0.119
		Outlet	62.4	0.312	29.1	1.057	54.5	0.272	25.4	0.923	7.9	0.039	3.7	0.134
Triton X 100 RBS 25	15.7	21 Inlet	85.8	0.429	40.0	1.454	76.7	0.383	35.7	1.299	9.1	0.045	4.2	0.154
		Outlet	51.7	0.258	24.1	0.876	45.9	0.229	21.4	0.778	5.8	0.029	2.7	0.098
		22 Inlet	83.4	0.417	38.9	1.413	77.0	0.385	35.9	1.305	6.4	0.032	3.0	0.108
		Outlet	47.3	0.236	22.0	0.801	42.4	0.212	19.8	0.718	4.9	0.024	2.3	0.083
Modified Plunger	15.7	29 Inlet	90.8	0.454	42.3	1.538	87.5	0.437	40.8	1.482	3.3	0.016	1.5	0.056
		Outlet	49.1	0.245	22.9	0.832	45.3	0.226	21.1	0.767	3.8	0.019	1.8	0.064
Modified Plunger & Exhaust Pre-cooler	15.7	30 Inlet	71.9	0.359	33.5	1.218	68.5	0.342	31.9	1.161	3.4	0.017	1.6	0.058
		Outlet	39.2	0.196	18.3	0.664	34.9	0.174	16.3	0.591	4.3	0.021	2.0	0.073
--	8.8	18 Inlet	80.4	0.402	37.5	1.362	76.0	0.380	35.4	1.288	4.4	0.022	2.0	0.075
		Outlet	50.1	0.250	23.3	0.849	44.7	0.223	20.8	0.757	5.4	0.027	2.5	0.091
		19 Inlet	58.3	0.291	27.2	0.988	53.2	0.266	24.8	0.901	5.1	0.025	2.4	0.086
		Outlet	42.8	0.214	19.9	0.725	39.8	0.199	18.5	0.674	3.0	0.015	1.4	0.051

*Test not included in average particulate levels

APPENDIX II

Chemical Additives to Scrubber Water to Improve NO_x Collection

1. CHEMICAL SELECTION

A literature search was carried out to determine the best potential chemical additives for this purpose. This was followed by a laboratory study using a synthetic gas stream under space velocity conditions and temperatures for a practical wet scrubber for diesel exhaust control.

Seven chemical additives were selected from the literature search for a preliminary screening of their effectiveness using a 1:1 ratio of $NO:NO_2$ at a concentration of 600 ppm NO_x. These were urea, acidified urea, magnesium carbonate, calcium oxide, sodium hydroxide, ammonium carbonate and ammonium sulfate/sulfite/bisulfite. From these results, the best three chemical additives were selected for further testing using different ratios of $NO:NO_2$ to cover the range observed in practice from the emissions of a Deutz diesel engine.

2. TEST PROCEDURE

Synthetic gas mixtures of NO_x in a N_2/O_2 carrier with oxygen concentrations of about 10% were heated to about 300 - 350°C and passed into either a cold or warm aqueous scrubber containing the chemical additive to be tested.

3. SCREENING TESTS OF SEVEN CHEMICAL ADDITIVES

The percentage removal of NO and NO_2 were calculated for each of the experiments and is compiled in Table A.1. The scrubber temperature was allowed to drift to an equilibrium value as determined by the gas stream temperature and the chemical reactions in the scrubber. The range in temperature obtained is included in Table A.1 together with the temperature range of the gas stream from the beginning to the conclusion of each run. The range of values obtained for NO and NO_2 removal from beginning to conclusion of the run is also detailed.

The contents of Table A.1 are further summarized in Table A.2 which gives the percentage removal of NO and NO_2 by the various scrubber additives after 60 minutes. A comparison of the results between the cold scrubber (14-16°C) and warm scrubber (32-41°C) is presented.

Generally speaking, the hot gas stream (300-350°C) and warm scrubber caused no significant increase or decrease in the percentage removal of NO or NO_2 by any of the additives, from the results carried out at ambient temperatures. The one exception to this is the calcium oxide additive.

Using a hot gas stream and a scrubber which is warmer by 22°C, the NO removal decreased by 20% and the NO_2 removal decreased by 27%.

The percentage removal of NO and NO_2 by the various additives to the aqueous scrubber are plotted against time in Figures A.1 - A.4.

Figures A.1 and A.2 show the percentage removal of NO_2 by a cold scrubber (14-16°C) and by a warm scrubber (32-41°C), respectively.

Figures A.3 and A.4 depict the percentage removal of NO by the same cold and warm scrubber, respectively.

To normalize each of the experiments, the percentage removal of NO_2 or NO is marked on Figures A.1 - A.4 after 60 minutes of wet scrubbing (Table A.2).

From the results the three best chemical additives for removal of both NO and NO_2 were determined to be sodium hydroxide, calcium oxide and ammonium carbonate when using a 1:1 ratio of $NO:NO_2$. Further tests of these three chemicals were therefore carried out at differing ratios of NO to NO_2.

4. NO_x SCRUBBING EFFICIENCIES vs NO/NO_2 RATIO

Figures A.5 - A.9 show the effect of NO/NO_2 ratios varying

from 1:1 to 7:1 on the scrubbing efficiencies of the three selected additives for removal of both NO and NO_2. The results are summarized as follows.

4.1 Sodium Hydroxide

From Figures A.1 and A.2 it is readily observed that this particular chemical additive performs its best at low temperatures. When the scrubber temperature was elevated from 19°C to 47°C, the amount of NO_2 removal dropped by 27% and NO removal by 26%. However, even when warm, it removed 50% NO_2 and 46% NO after one hour and still ranked in the top three for its efficiency of removal of oxides of nitrogen.

The tendency to froth is reduced upon exposure to nitrogen dioxide and the time period required for control of the head of bubbles seemed to be inversely proportional to the concentration of NO_2.

Sodium hydroxide was also tested at ratios of 3:1 and 7:1 of NO:NO_2 and compared with the results obtained at a 1:1 ratio (Figures A.5, A.6).

It was found to remove 86% NO_2 at a ratio of 7:1 (77 ppm NO_2, 34°C) while at a ratio of 1:1 (300 ppm NO_2) it was found to remove 77% at 19°C decreasing to 50% NO_2 at a higher scrubber temperature of 47°C (Figure A.5). The NO_2 results for the 3:1 ratio experiment could not be determined since the readout of total oxides of nitrogen was lower than NO.

The ability of NaOH to remove NO, on the other hand, decreases when the ratio is increased from 1:1 through 7:1 (Figure A.6). The percentage removal of NO decreased from 46% (1:1), to 20% (3:1) to 13% (7:1). Therefore its ability to remove NO and total oxides of nitrogen is enhanced by the presence of larger amounts of NO_2.

4.2 Calcium Oxide

This chemical additive to water is also excellent for removal of both NO and NO_2. As with NaOH, it was found to perform most effectively at the lower temperatures (Figures A.1 - A.4). The amount of nitrogen dioxide removed decreased from 81% using a cold water scrubber (16.5°C) to 54% using a warm water scrubber (38.5°C). At the same time, the amount of NO removed decreased from 58% in a cold scrubber to 38% in a warm scrubber. Calcium oxide ranked third among the chemical additives tested for removal of NO using a 1:1 ratio of 300 ppm NO plus 300 ppm NO_2 (Figures A.3 - A.4) and ranked second for removal of NO_2.

The percentage removal of NO_2 and NO by calcium oxide using ratios of 1:1, 3:1 and 8:1 of NO:NO_2 is shown in Figures A.7 and A.8. The percentage removal of nitrogen dioxide increased with decreasing concentration. For ratios of 1:1, 3:1 and 8:1, the percentage removal was calculated to be 54%, 55% and 69%, respectively. This trend was also observed with NO, i.e. the percentage removal decreased with increasing concentration of NO. The values obtained were 38%, 21% and 14% removal of NO for ratios of 1:1, 3:1 and 8:1 of NO:NO_2, respectively.

This is the same trend as was observed with the sodium hydroxide scrubbing media. The total amount of NO_x removed is shown in Table A.3 for each ratio of NO:NO_2 using a hot gas stream and a warm scrubber. Both sodium hydroxide and calcium oxide performs in a similar manner with percentage removal decreasing from 48 to 22% and 46 to 20%, respectively, as the NO:NO_2 ratio increased.

4.3 Ammonium Carbonate

This additive to scrubber water ranked in the top three for removal of NO and NO_2 by both cold and hot scrubbing solutions when using a 1:1 ratio of NO to NO_2. However, the data obtained from

investigating the effects of NO in the presence of ammonia upon the moly converter readout could explain why this scrubbing solution gave such a high efficiency of removal of NO. Nonetheless, even if an error of 25% was introduced by a reaction of NO and ammonia in the converter, this scrubbing media would still rank third for its efficiency of removal of oxides of nitrogen.

When this scrubber solution was tested at a different $NO:NO_2$ ratio (3:1), a frothing problem developed which did not disappear with a slight decrease of the volume or the concentration of the solution. Results were obtained using only 50 ml of scrubbing solution for the 3:1 experiment and 100 ml solution for the 6.4:1 experiment. Since NO_x values were 100-160 ppm less than NO values, only the NO values have been plotted (Figure A.9). The percentage removal of NO decreased with increasing concentration of NO and $NO:NO_2$ ratio (60 → 15%).

The values of percentage removal of NO, NO_2 and NO_x shown in Table A.3 for ammonium carbonate are not too meaningful because a significant disappearance of NO in the moly converter was occurring.

5. CONCLUSIONS

In summary, any of the results presented which contain ammonium compounds in the scrubber solution are not accurate due to a chemical reaction which seems to be occurring in the moly converter to remove NO.

Both sodium hydroxide and calcium oxide have approximately the same efficiency of removal of NO and NO_2 using different ratios of $NO:NO_2$. However, CaO has better merit than NaOH for underground use from a safety viewpoint. Both have increased efficiency of removal at lower temperatures if they could be cooled in actual practice.

Urea, acidified urea and magnesium carbonate scrubbing solutions

remove a moderate amount of NO_2 (32-47%) but only 4-21% of NO, using a 1:1 ratio of $NO:NO_2$.

All of the additives to water were better than water for removal of oxides of nitrogen.

Frothing tendencies were exhibited by ammonium carbonate, ammonium sulfite: bisulfite and by sodium hydroxide. However, the frothing subsides in the NaOH scrubber after a few mintues of exposure to NO_2. In a different scrubber design, the longer residence time of the gas stream in contact with the bubbles could be employed to advantage to increase scrubber efficiency.

TABLE A.1

A Comparison of the Percentage Removal of NO and NO_2 by Various Additives to Cold and Warm Aqueous Scrubbers Using a Gas Stream Containing 300 ppm NO plus 300 ppm NO_2 After 60 minutes of Wet Scrubbing

Additive	Concentration W/V (%)	% Removal of NO		% Removal of NO_2	
		Cold (14-16°C)	Warm (32-41°C)	Cold (14-16°C)	Warm (32-41°C)
Water	-	(<0)	6	(38)	22
	-	-	0	-	14
Urea	10.0	4	13	41	41
Urea (acidified)	10.0	18	21	45	38
Magnesium Carbonate	3.4	16	-	44	-
	3.7	-	19	-	45
Calcium Oxide	3.4	58	-	81	-
	10.0	-	(38)	-	(54)
Sodium Hydroxide	10.8*	67	-	70	-
	10.8*	53	-	63	-
Ammonium Carbonate	9.8	65	59	82	82

( ) denotes an extrapolated value for 60 minutes

* A lesser volume of 100 ml and 200 ml, respectively, was used because of frothing. A volume of 300 ml was used for all other experiments.

TABLE A.2

A Comparison of the Percentage Removal of NO and NO_2 from a Gas Stream Containing 300 ppm NO and 300 ppm NO_2 and Depiciting the Range in Values Obtained for Temperature and Percentage Removal During Each Experiment

Additive	Concentration W/V (%)	Temperature (^oC)		Percentage Removal of	
		Scrubber	Gas Stream	NO	NO_2
Water	-	15.5	20	10.2-(+3.1)	32.9 - 37.5
	-	27 - 37.5	232 - 313	33.3 - 6.2	54.4 - 21.5
	-	33 - 40.5	348 - 365	6.6 - 0	25 - 10
Urea	10.0	24 - 15	20	28.3 - 0	45 - 40
	10.0	30 - 41	290 - 344	7.7 -13.2	30.5 - 41.4
Urea (acidified)	10.0	23 -	20	16.1 -17.7	41.8 - 45.6
	10.0	31 - 38.5	330 - 356	16.9 -20.0	35.2 - 44.1
$MgCO_3$	3.4	22.5 - 15	20	20.3 -15.6	42.2 - 43.8
	3.7	23 - 38	338 - 343	27.4 -23.3	48.3 - 48.6
CaO	3.4	27 - 16.5	20	54.1 -57.5	77.2 - 81.6
	10.0	30 - 38.5	345 - 350	46.2 -37.9	60.4 - 53.3
NaOH	10.8*	34 - 14	20	64.5 -67.5	66.7 - 70.1
	10.8**	20 - 16	28 - 27	51.3 -52.6	46.0 - 63.0
Ammonium Carbonate	9.8	18 - 16	29 - 27	58.5 -66.9	75.5 - 84.1
	9.8	18 - 32.5	180 - 334	64.1 -59.5	80.4 - 81.4

Note: (1) 300 ml aqueous scrubbing solution was used for all runs except:
* 100 ml
** 200 ml
(2) The range of figures reported are the initial and final values for each test.

TABLE A.3

A Comparison of the Percentage Removal of NO, NO_2 and NO_x from a Hot Gas Stream (300-350°C) by Three of the Most Efficient Scrubber Additives At a Concentration of 600 ppm NO_x using Variable Ratios of $NO:NO_2$

Chemical Additive	Concentration w/v (%)	Ratio $NO:NO_2$	Concentration		Efficiency of Removal of:		
			NO (ppm)	NO_2 (ppm)	NO (%)	NO_2 (%)	NO_x (%)
Sodium Hydroxide	10.0	1:1	315	315	46	50	48
	10.0	3.4:1	461	137	20	?	(35)
	10.0	7:1	538	77	13	86	22
Calcium Oxide	10.0	1:1	316	328	38	54	46
	10.0	3.3:1	475	145	21	55	31
	10.0	8.3:1	539	65	14	69	20
Ammonium Carbonate	9.8	1.3:1	365	275	59	82	69
	10.0	3:1	460	150	33*	?	(67)
	8.5**	3:1	449	163	15	?	(29)
	8.5***	6.4:1	541	85	12	?	(31)

? = NO_x < NO and therefore NO_2 could not be calculated
( ) = % removal of NO_x calculated although NO_x < NO
* = Value obtained at 18 mins. when frothing resulted in abandoning the run
** = 50 ml scrubbing solution
*** = 100 ml scrubbing solution

FIGURE A.1

Percentage NO_2 Removal By Additives To Cold Water Scrubber; Gas Stream At Ambient Temperature, And Concentration Of 300 ppm NO + 300 ppm NO_2

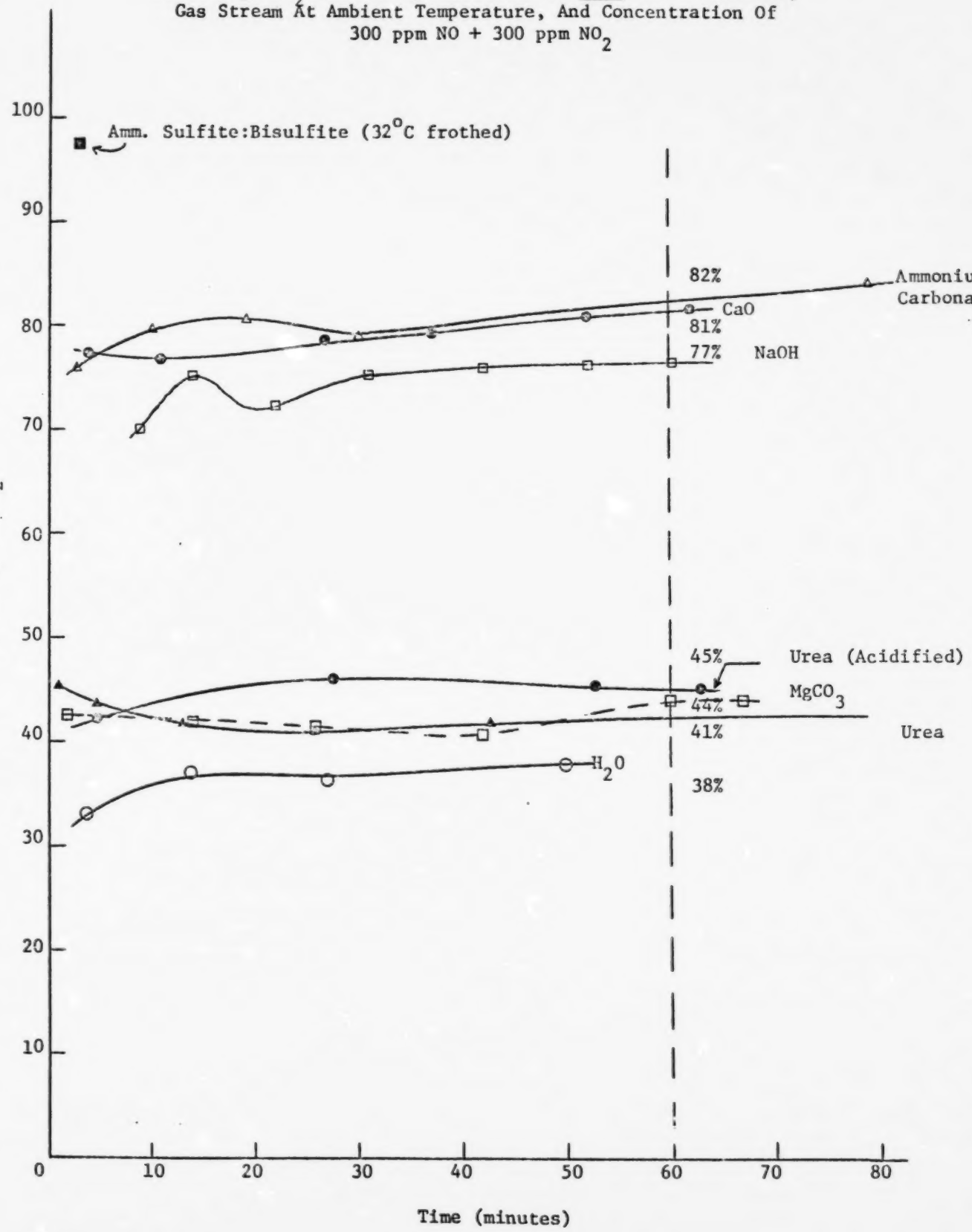


FIGURE A.2

Percentage NO_2 Removed By Additives To Warm Aqueous Scrubber; Gas Stream at 300 - 350°C and Concentration of 300 ppm NO + 300 ppm NO_2

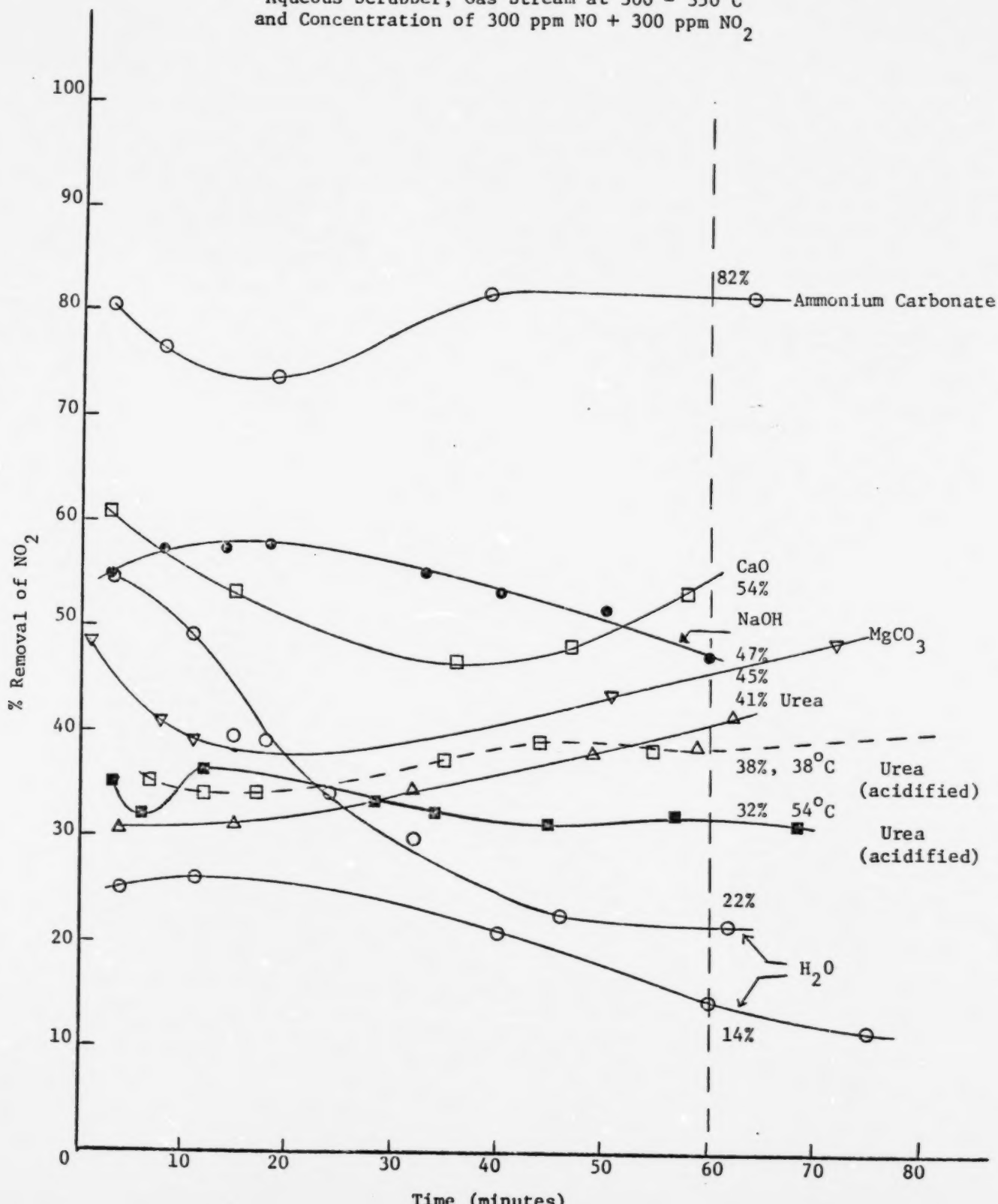


FIGURE A.3

Percentage NO Removed By Additives To Cold Water Scrubber;
Gas Stream At Ambient Temperature and Concentration of
300 ppm NO + 300 ppm NO_2

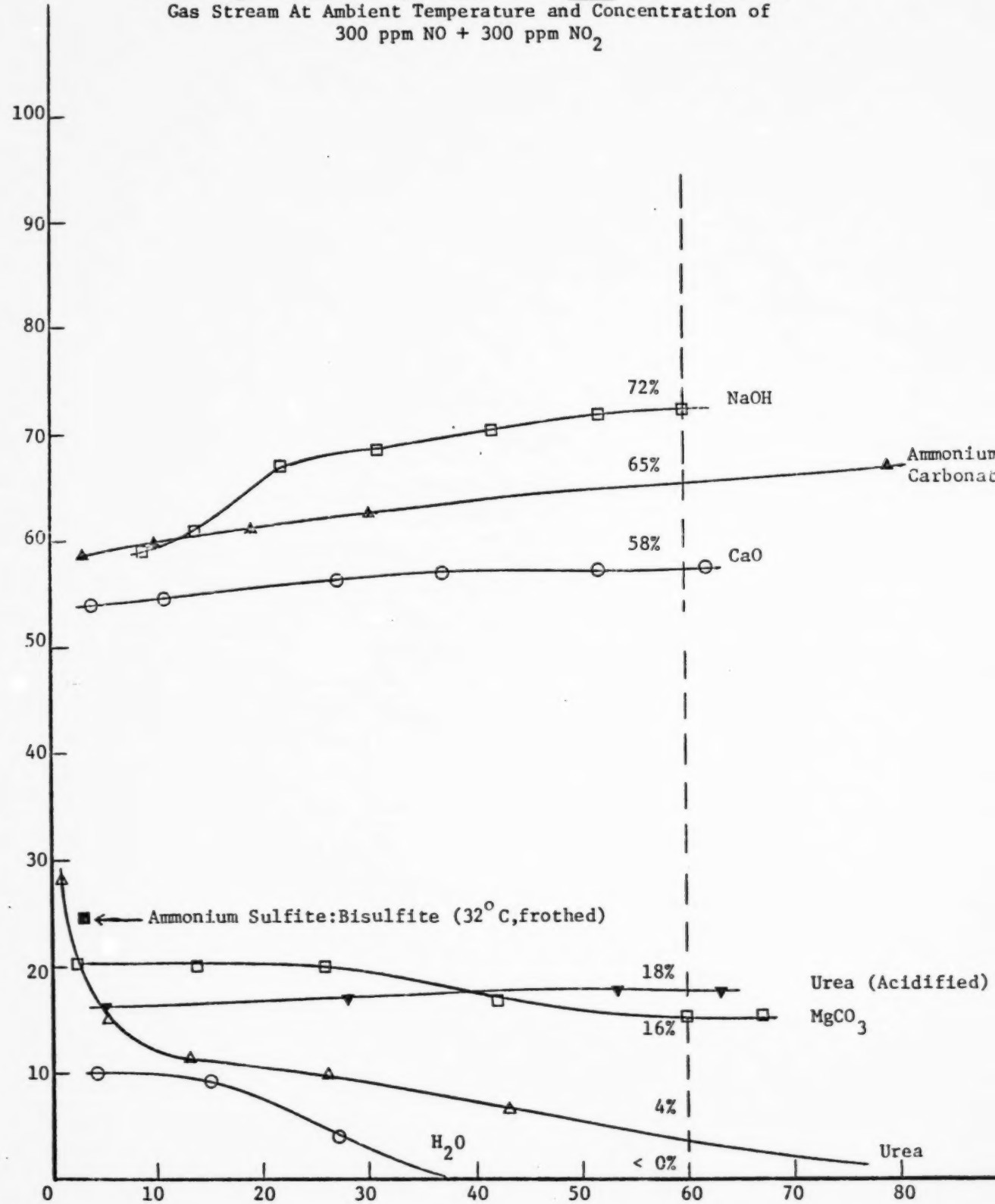


FIGURE A.4

Percentage NO Removed by Additives to Warm Aqueous Scrubber; Gas Stream at 300 - 350°C and Concentration of 300 ppm NO + 300 ppm NO_2

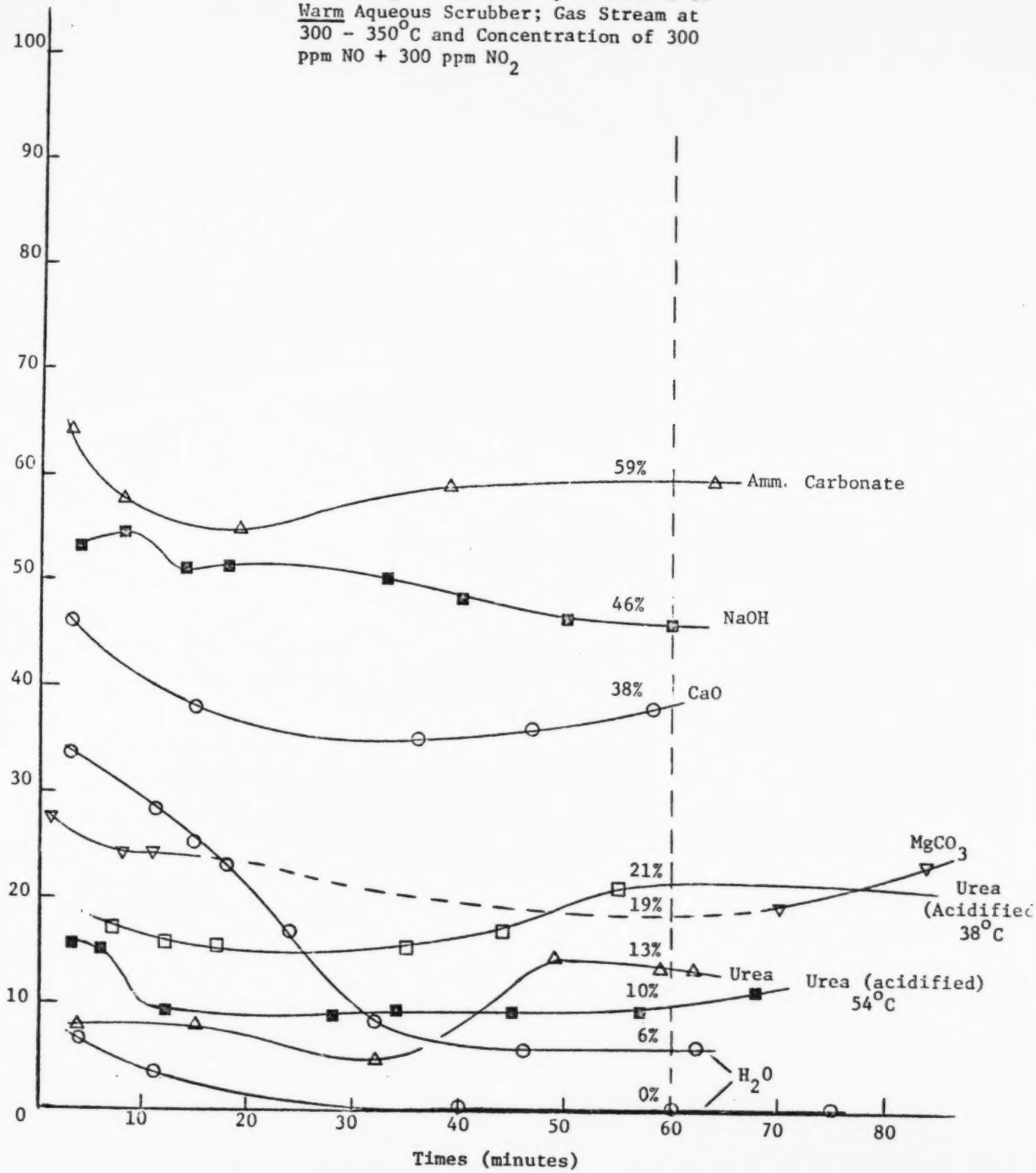


FIGURE A.5

Comparison of Percentage Removal of NO_2 by 300 ml NaOH (10% w/v) at Different Ratios of $NO:NO_2$ (600 ppm NO_x) and Different Scrubber Temperatures

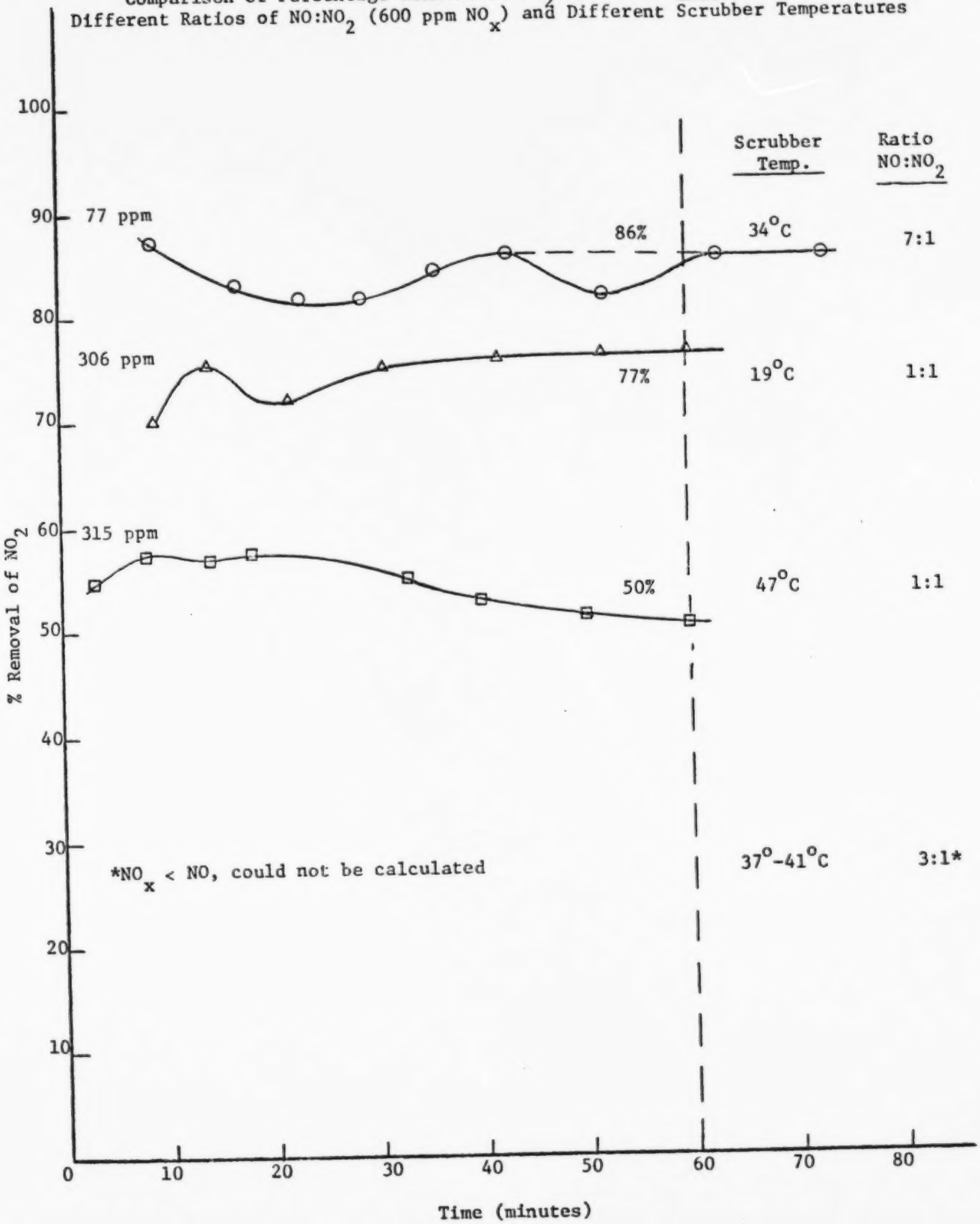


FIGURE A.6

Percentage Removal of NO by 300ml NaOH (10% w/v) at Different Ratios of $NO:NO_2$ (600 ppm NO_x) Using a Warm Scrubber

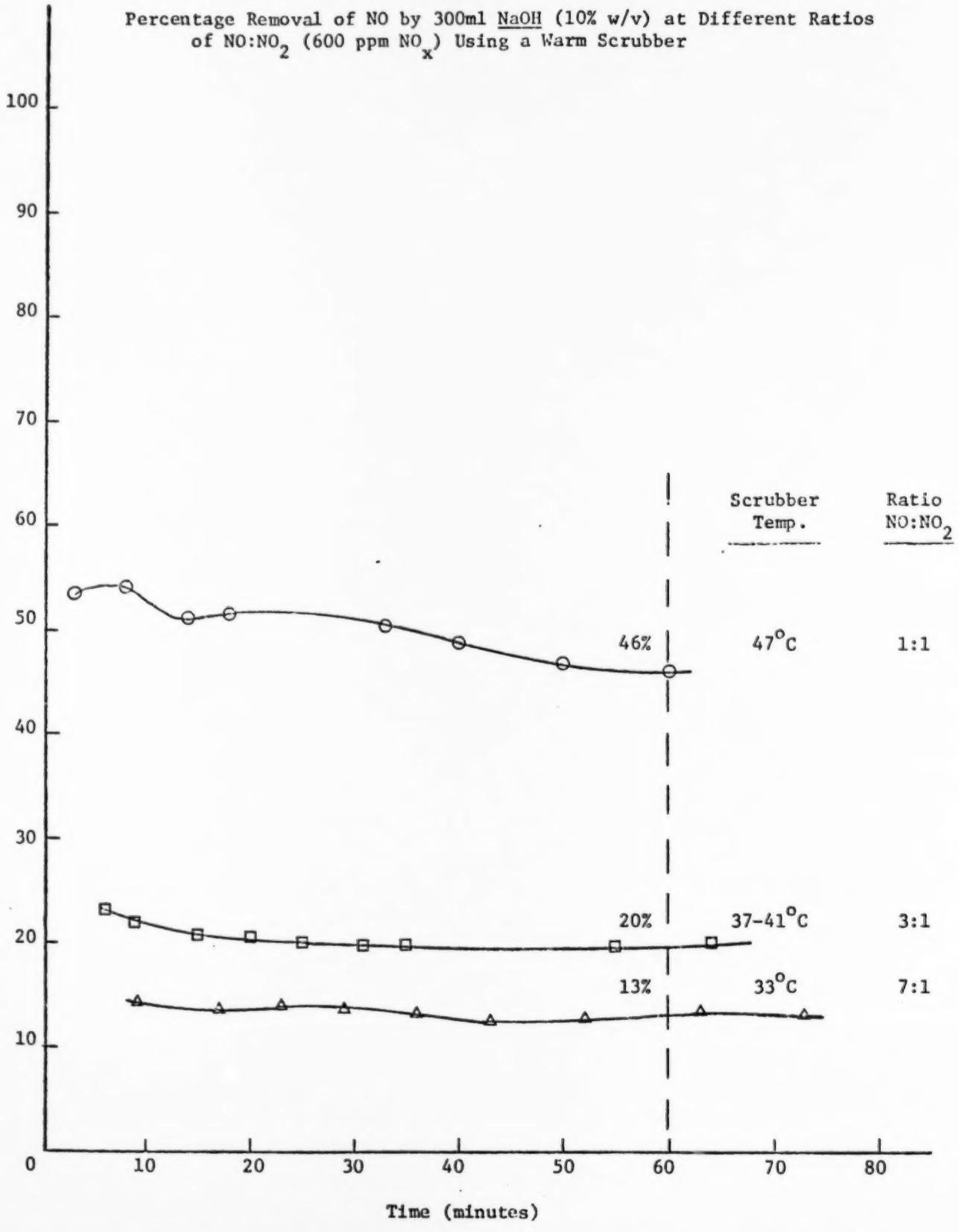


FIGURE A.7

Percentage Removal of NO_2 by CaO (10% w/v) at Different Ratios of $NO:NO_2$ (600 ppm NO_x) Using a Warm Scrubber

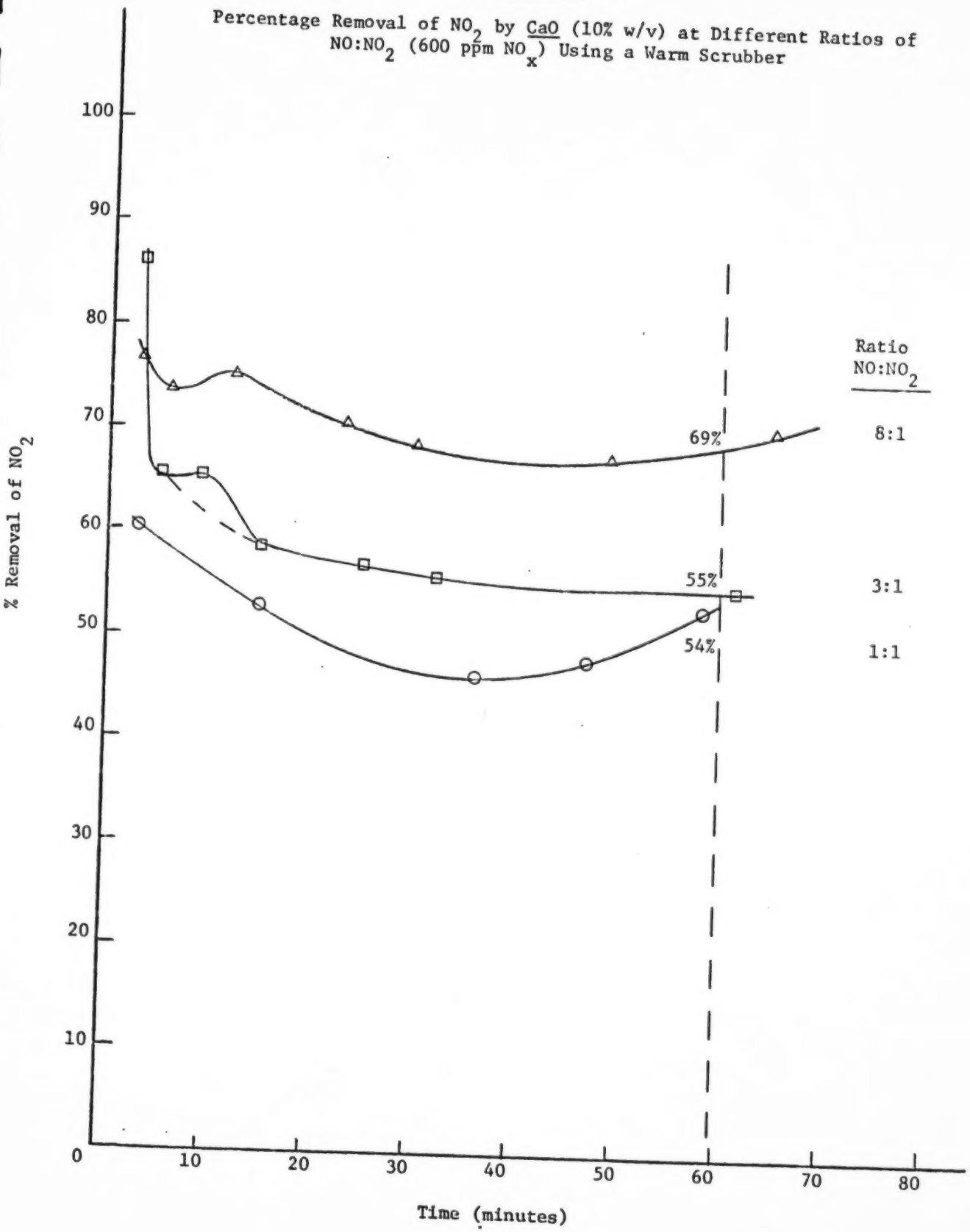


FIGURE A.8

Percentage Removal of NO by Calcium Oxide (10% w/v) at Different Ratios of $NO:NO_2$ (600 ppm NO_x) Using a Warm Scrubber

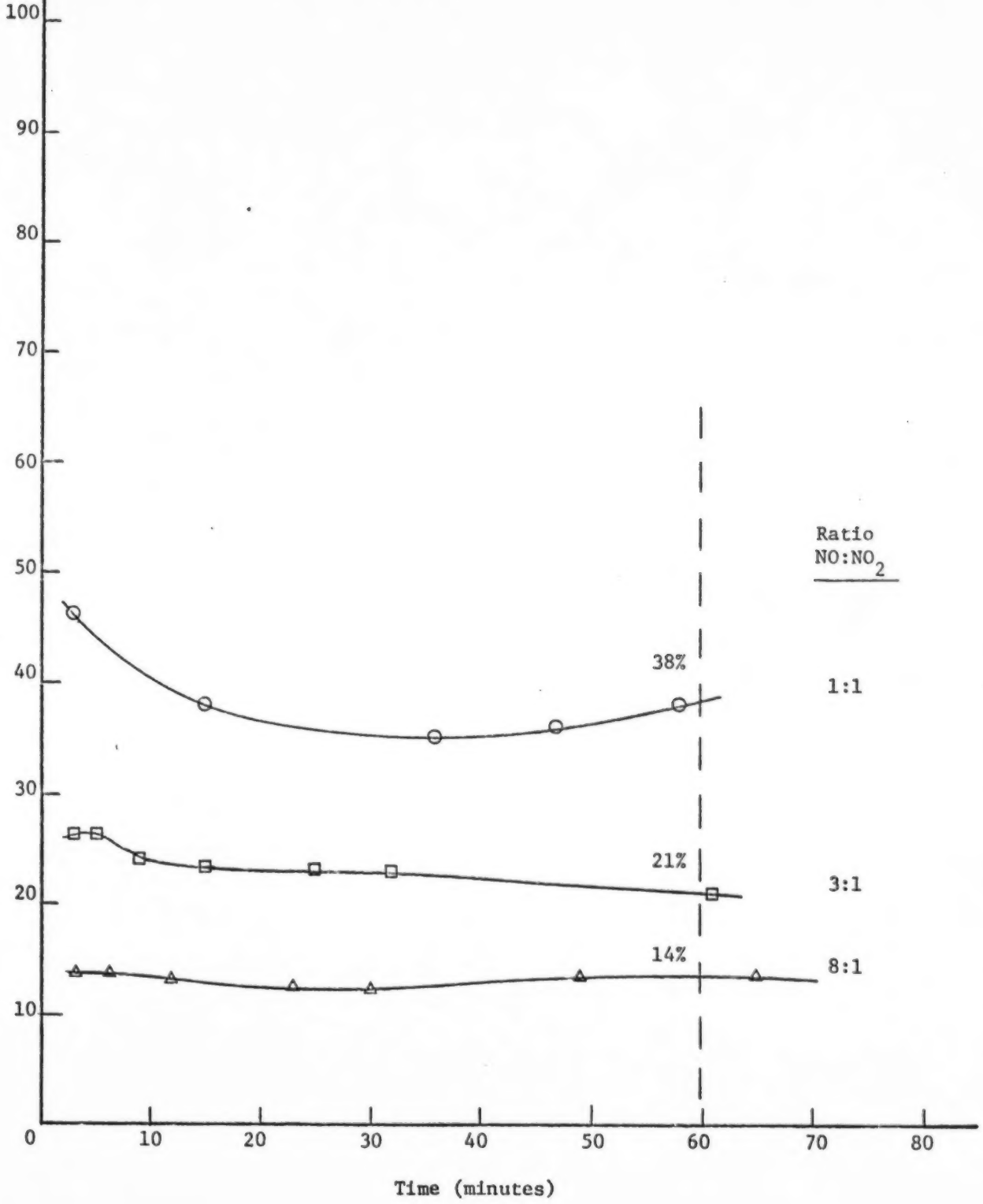
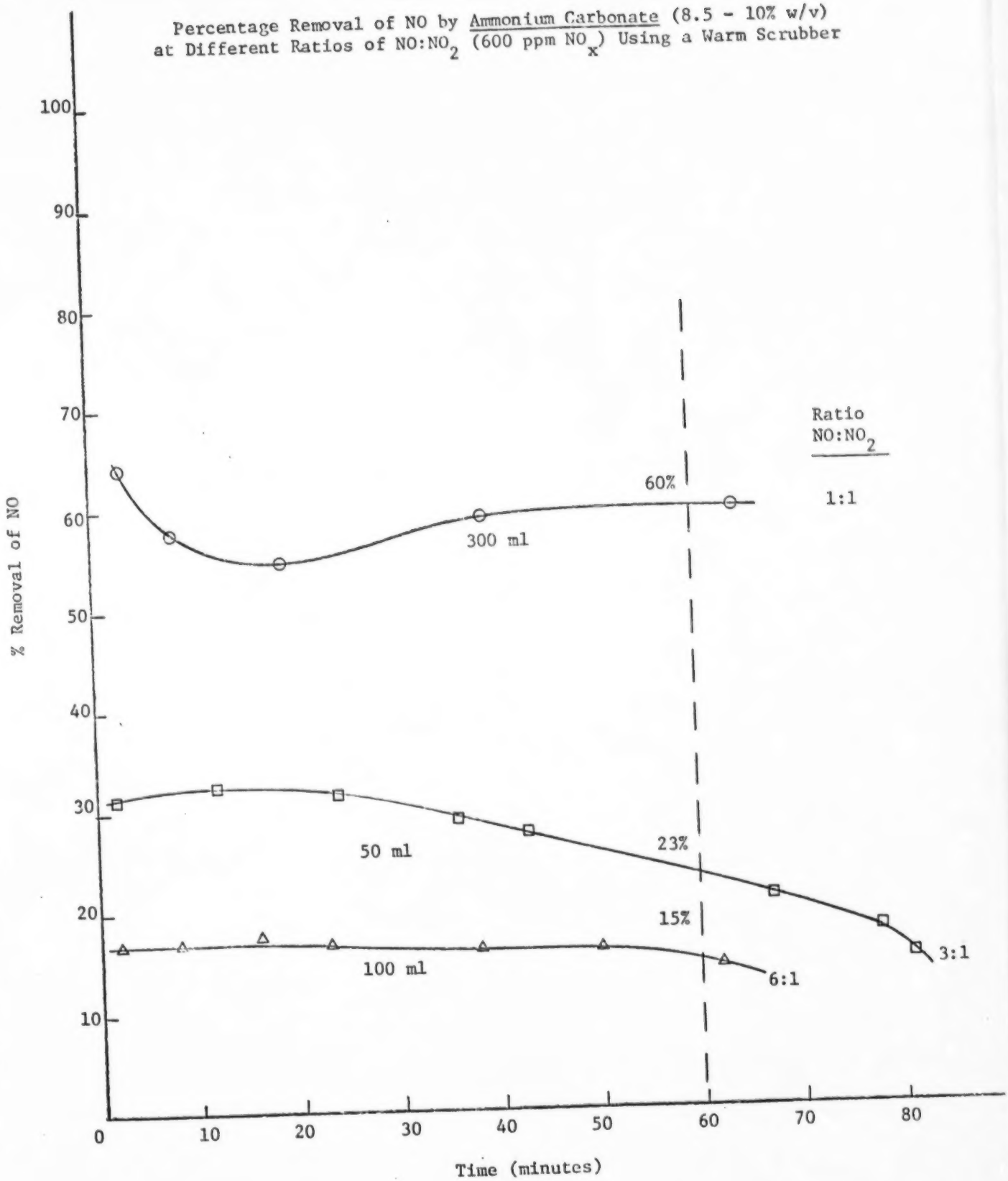


FIGURE A.9

Percentage Removal of NO by Ammonium Carbonate (8.5 - 10% w/v) at Different Ratios of NO:NO_2 (600 ppm NO_x) Using a Warm Scrubber



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